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STUDY OF THE VTOL DOWNWASH IMPINGEMENT PROBLEM

Project 9R38-01-017-29

Contract DA-44-177-TC-689

November 1960

prepared by :

CORNELL AERONAUTICAL LABORATORY, INC.
Buffalo, New York

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STUDY OF THE VTOL DOWNWASH IMPINGEMENT PROBLEM

C.A.L. Report No. BB-1467-S-1

Prepared by

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FOREWORD

The project work described in this report was accomplished by the Cornell Aeronautical Laboratory, Inc., Buffalo, New York for the VTOL/STOL Design Criteria Branch of the Aero-Mechanics Division, U. S. Army Transportation Research Command, Fort Eustis, Virginia. The work was accomplished under Project 9R38-01-017 and Task No. 29, "Study of VTOL Downwash Impingement Problem". Mr. Richard P. White, Jr. of C.A.L. was project engineer and Mr. Robert Graham, Chief, VTOL/STOL Design Criteria Branch of the Aero-Mechanics Division, administrated the project for TRECOM. The work started on 11 July 1960 and was completed on 1 December 1960.

Appreciation is extended by the authors to H. Daughaday, F. DuWaldt, E. Engel, R. Hartunian, C. Mayerson, C. Notess, and A. Sowyrda of C.A.L. for their significant contributions to the investigation.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF SYMBOLS

g Acceleration due to gravity

H_o Height of actuator disk above the ground

q Dynamic pressure of flow parallel to the ground

q_{MAX} Maximum dynamic pressure at jet stagnation point

r Radius of ground particles

R Radius of downwash cylinder

R_o Radius of actuator disk

$\left(\frac{R}{R_j}\right)_{MAX}$ Radial position of q_{max}

T Thrust

V Freestream velocity

δ Boundary layer thickness

ρ Air density

ρ_s Density of solid ground particles

SUMMARY

This report describes the work that was undertaken by Cornell Aeronautical Laboratory, Inc. during an intensive review and analysis of the problems associated with dust and debris entrainment in the downwash of helicopters and other VTOL configurations during "near ground" operations.

The first section of the report presents a review of present knowledge concerning the nature of downwash impingement. The next section of the report presents a list and brief description of suggested programs which have one of the following objectives: (1) to obtain a better understanding of the problem, (2) to investigate ideas that have been proposed to reduce the entrainment and detrimental effects of particles, and (3) to investigate ideas that have been proposed for avoiding entrainment of objects by the downwash. The final section of the report presents a series of investigations that are recommended to accomplish one or more of the above objectives. For each of the recommended investigations, the purpose, a brief discussion, and suggested scope are presented.

1

I   INTRODUCTION

In recent years, a number of new types of VTOL aircraft have been proposed and constructed and, although several of these are now under flight evaluation, little is known concerning the magnitude of the downwash impingement problem for these new vehicles. At present, for example, operational limits for the avoidance of downwash impingement are not well defined even for the helicopter. However, the difficulties associated with helicopter operations over unprepared areas have focused attention on specific problems which should also be the principal problems due to downwash impingement of other VTOL configurations. Some of these principal problems are, for example, loss of pilot visibility, damage to rotating and nonrotating parts of the vehicle, injury to personnel, and loss of concealment.

There are a variety of thrusting systems used in VTOL configurations to generate static lift. Examples of these are the rotor, the ducted fan, the tilted propeller, the exhaust from a turbojet engine, etc. Neglecting the rotational velocities in the downwash, it can be seen that the configurations differ only in disk loading and its distribution, and in the jet temperature. The jet temperature is important in the downwash impingement problem only in that the impinging jet will heat the ground plane and alter its mechanical properties. Hence, the downwash impingement problem for all configurations cited above can be considered by replacing them by an equivalent jet, and considering the effects of jet velocity on the fundamental problem of entraining ground particles.

Operational experience on the downwash impingement problem has been limited almost entirely to the helicopter which has the lowest disk loading and downwash velocity of the various VTOL configurations considered herein. In spite of the low disk loading of the helicopter, it has been found capable of picking up considerable quantities of dust and debris when hovering over dry sand or loose dirt.

In the case of the helicopter, the clouds of dust or sand which are created by the downwash impingement, while not forcing a complete stop to operations, have made them far more inefficient and dangerous. The abrasive effects of sand on rotating parts such as the tail rotor have been serious, particularly in desert operations. In addition, nonrotating parts of helicopters have been damaged; in particular, plexiglas bubbles and antenna installations on the underside of the fuselage. The ingestion of sand into the engine due to the entrainment of debris during desert operations has necessitated frequent overhauls. In the case of turbines, the larger particles that are entrained have caused serious damage.

In addition to being subjected to the nuisance of getting dust in their eyes, personnel have been injured by being struck by pebbles and small debris picked up by the deflected air jet. Larger objects on the ground (pieces of wood, equipment, etc.) are also potentially dangerous when hurled by the air blast.

Many military operations require that a helicopter's location remain unknown to the enemy. Thus, the loss of concealment resulting from large clouds of dust must be avoided insofar as possible. This may be the most difficult problem to solve of those which have been mentioned.

Cornell Aeronautical Laboratory has undertaken an intensive review and analysis of the problems associated with dust and debris entrainment in the downwash of the helicopters and other VTOL configurations during "near ground" operations. The over-all objectives of this program have been: (1) to seek a qualitative understanding of the factors leading to particle entrainment in the downwash, (2) to recommend areas of research that hold promise for a fundamental understanding and solution to the problem, and (3) a definition of methods by which the problems associated with the impingement of downwash may be alleviated. This report summarizes the work that was undertaken during this program. The first section of the report presents a review of present knowledge concerning the nature of downwash impingement. The second part of the report presents a list of possible investigations for studying the downwash impingement problem. In keeping with the above objectives, the final section of the report presents a description of the programs that are recommended for further research.

3

II REVIEW OF PRESENT KNOWLEDGE CONCERNING
THE NATURE OF DOWNWASH IMPINGEMENT

All types of VTOL vehicles obtain lift at near zero flight velocities from the reaction which results from continually forcing a mass of air downward and it is evident, therefore, that downwash impingement is unavoidable in operations near the ground. Many downwash impingement phenomena are common to all VTOL vehicles but some difference would be expected for different configurations. It is believed, however, that there is a sufficient area of similarity between the downwash produced by rotors, propellers, turbojets, and ducted fans, to make it feasible to consider them simultaneously. These configurations would include the helicopter, rotatable ducted fans, tilt wings, tilting propellers, fan in wing, etc. The flow phenomena for deflected slipstream and jet flap configuration are entirely different and will be treated separately.

In respect to underlying principles, the present status of knowledge concerning the effects of downwash impingement resulting from VTOL vehicles which utilize rotors, propellers, or ducted fans, is fairly comprehensive. This fact will be demonstrated herein by separating the complicated real jet impingement problem into simplified component flows for which theories are available, and comparing results based on these theories with experiments. Qualitative agreement is achieved in most respects, although quantitative agreement with experiment is not sufficient for an adequate theoretical investigation of particle entrainment.

One basic aspect of the downwash impingement problem for which there is no quantitative or qualitative understanding is the process by which the particles are lifted from the ground and entrained in the main flow. With a sound understanding of this mechanism, it would, in principal, be possible to consider and to assess quantitatively various means for preventing particles from being entrained.

4

Consideration of the mechanism of particle entrainment requires a detailed knowledge of the flow near the ground. In particular, one must be able to predict the growth of, and the velocity distributions in, the boundary layer on the ground. This boundary layer solution depends on the impressed pressure distribution over the ground, which can be approximated by the pressure distribution corresponding to the inviscid flow field produced by the configuration. Hence, understanding of the entrainment process follows from consideration of: (1) the inviscid flow field of the configuration in ground effect, (2) the development of the boundary layer flow along the ground plane, and (3) the forces on ground particles in a nonuniform or boundary layer flow. The available theoretical and experimental data in each of these three areas will be reviewed in this section.

Inviscid Flow Field

The available literature (for example, References 1 - 6) show the general qualitative nature of the effect of a jet impinging on a ground plane. One important feature reported in Reference 4 is that a uniform jet impinging on the ground produced erosion and particle entrainment similar to that obtained with a lifting rotor. This indicates that the distribution of velocities within the jet may not be of paramount importance in the impingement phenomena. In many cases, therefore, it may be acceptable to approximate the flow field of a lifting rotor or jet by an ideal jet having a uniform velocity at the effective actuator disk.

The actual flow field of a jet near the ground is characterized by jet flaring with a radial flow along the ground, as shown in Figure 1. Since the downwash problem is ultimately concerned with the flow field near the ground plane, it is desirable to include this jet flaring in describing the inviscid flow field. There are no known theoretical solutions which include the effects of jet flaring and which can be used to calculate the flow field of a three-dimensional jet impinging on the ground. The usual approach is to neglect this aspect of the problem and to use the classical model of a jet in proximity with the ground to calculate the flow field, Figure 2. That is, the jet is replaced
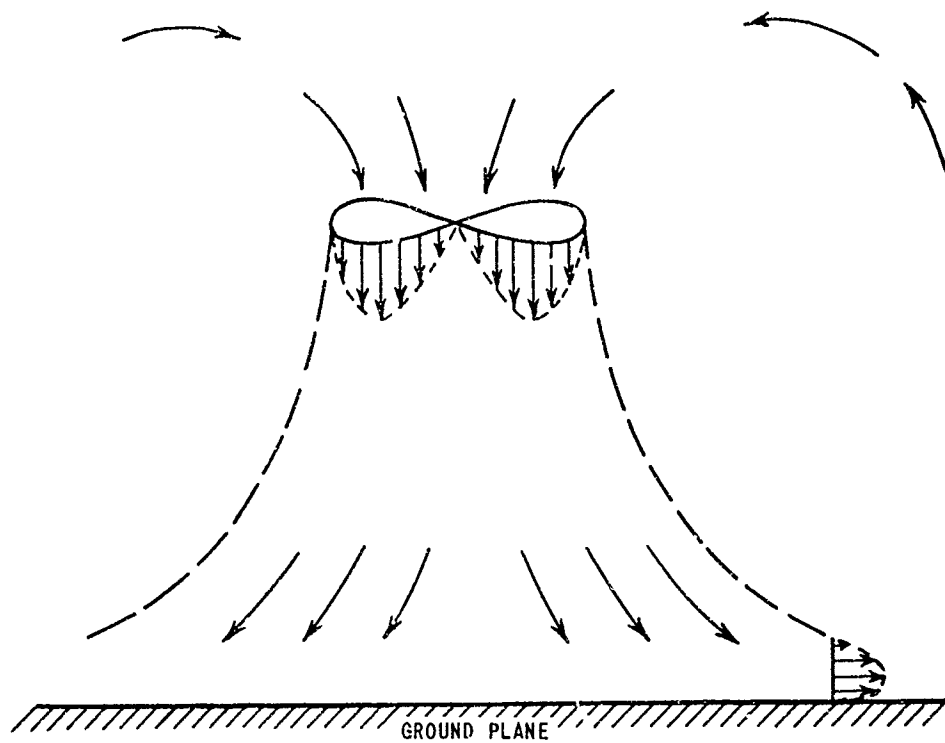
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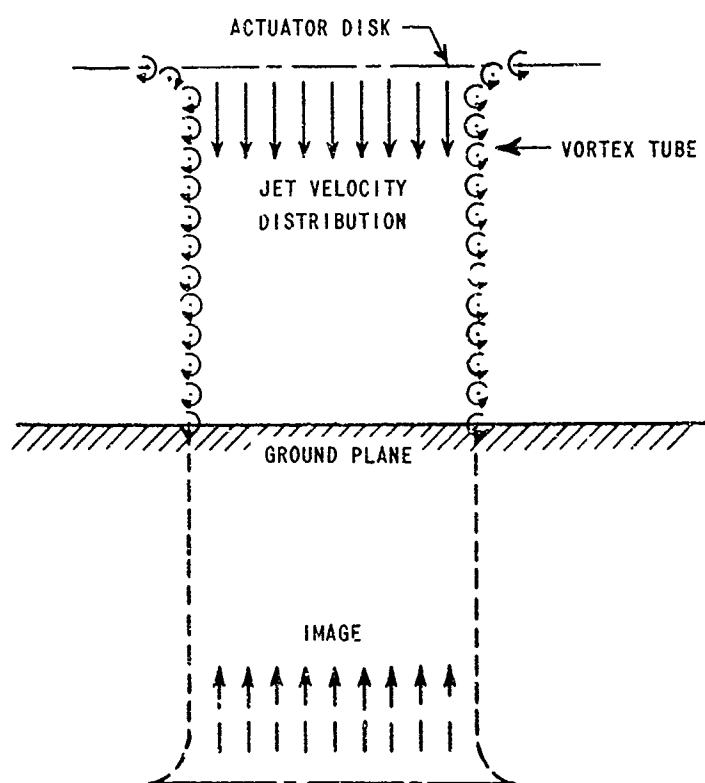Fig. I TYPICAL FLOW FIELD OF AN IMPINGING PROPELLER JET

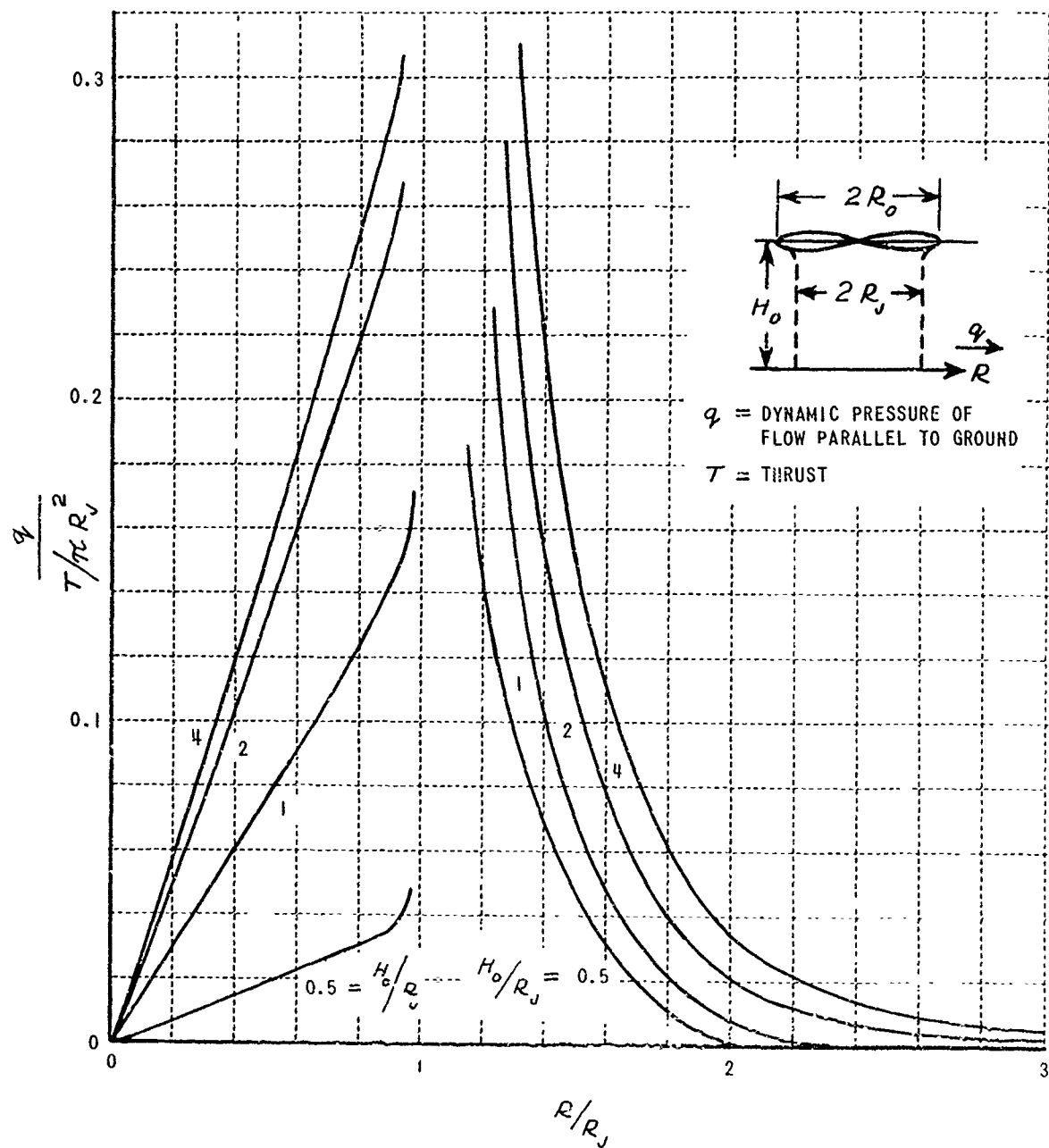

Fig. 2 CLASSICAL VORTEX MODEL OF AN IMPINGING JET

6

Fig. 3 DYNAMIC PRESSURE DISTRIBUTION OF THE FLOW PARALLEL TO THE
GROUND FOR VARIOUS DISK ELEVATIONS

by a cylindrical vortex sheet of a constant radius which extends to the ground. The ground plane is replaced by an equivalent image of the jet model. An important limitation of this model, regarding the present problem, is the lack of the similarity to the actual physical situation on the ground plane; indeed, the model of Figure 2 has a singularity on the ground plane at the edge of the jet which produces an infinite velocity at this point.

The distribution of dynamic pressure along the ground plane has been calculated using the classical model of Figure 2 and is shown in Figure 3 as a function of the disk height above the ground. It can be seen that the results are clearly inapplicable in the vicinity of $\frac{R}{R_j} \cong 1$ because of the singularity. The results, however, do qualitatively show the general trends to be expected. That is, they show a stagnation point at the center of the jet and the dynamic pressure increasing toward the edge of the jet. Outside of the jet, the dynamic pressure lls off rapidly because of continuity requirements.

The theoretical development and model (Figure 2) are lacking in two important aspects. The development does not include viscosity and, accordingly, the results do not include the effects of jet mixing. Also, the model does not include the effects of jet flaring when the jet strikes the ground. A meaningful comparison between theory and experiment can be obtained in spite of these differences by proper rormalization of the data.

One effect of jet flaring is to distort the flow along the ground so that the maximum dynamic pressure occurs at a radial station different from that predicted by theory. This effect of flaring can be removed, at least approximately, by normalizing with respect to the radial station at which the maximum dynamic pressure occurs.

The effects of jet mixing can be interpreted by considering the data for a free jet (for example, Reference 4). These data show that mixing by itself causes a decrease in dynamic pressure in the jet as one proceeds further from the nozzle. This suggests that the mixing effect could be approximately included in the case of an impinging jet by considering an equivalent system. This

8

equivalent system would be an inviscid jet with a decreased dynamic pressure. The decreased dynamic pressure would be equal to that in the viscous free jet at an axial station corresponding to the ground separation distance. Now considering the turning process when a jet impinges on the ground, the data of Reference 4 suggest that (for small ground separation distances) there is little viscous loss in the turning, and the peak dynamic pressure in the ground flow is equal to the dynamic pressure at the jet nozzle. In keeping with the above discussion of the free jet, the effects of jet mixing can be removed from experimental data by considering the ground flow to be caused by an equivalent inviscid jet with a dynamic pressure equal to the maximum dynamic pressure in the ground flow. The data can then be compared with inviscid theory by normalizing the measured dynamic pressure with respect to the maximum dynamic pressure in the ground flow. The theoretical dynamic pressures must then be normalized with the disk loading.

The experimental results of Reference 4 and the theoretical results of Reference 3, thus normalized, are compared in Figure 4. It can be seen that the theory and experiment are in qualitative agreement in that the experimental trends are predicted by this simplified theory. It is noteworthy that the increase in ground dynamic pressure with increasing jet height is predicted. However, the quantitative agreement is very poor. This is believed to be due, primarily, to the neglect of the flaring of the jet in the vicinity of the ground.

It is noted that jet mixing and dissipation are important in determining the flow field of an impinging jet. It was of importance in the correlation in Figure 4 because the experiments were made with jet-ground separation distances of one and two diameters where jet dissipation effects first become important. For smaller ground separation distances, the effects of jet dissipation can often be neglected. It has been found, in the present survey, that jet dissipation cannot be predicted with good accuracy for all separation distances using the available theories (for example, Reference 7). It was found that this theory was quantitatively accurate for uniform jets at large ground separation distances (more than four diameters) and for high disk loadings (500-2000 p.s.f.). At lower disk loadings, the theory proved accurate only if the free constant was
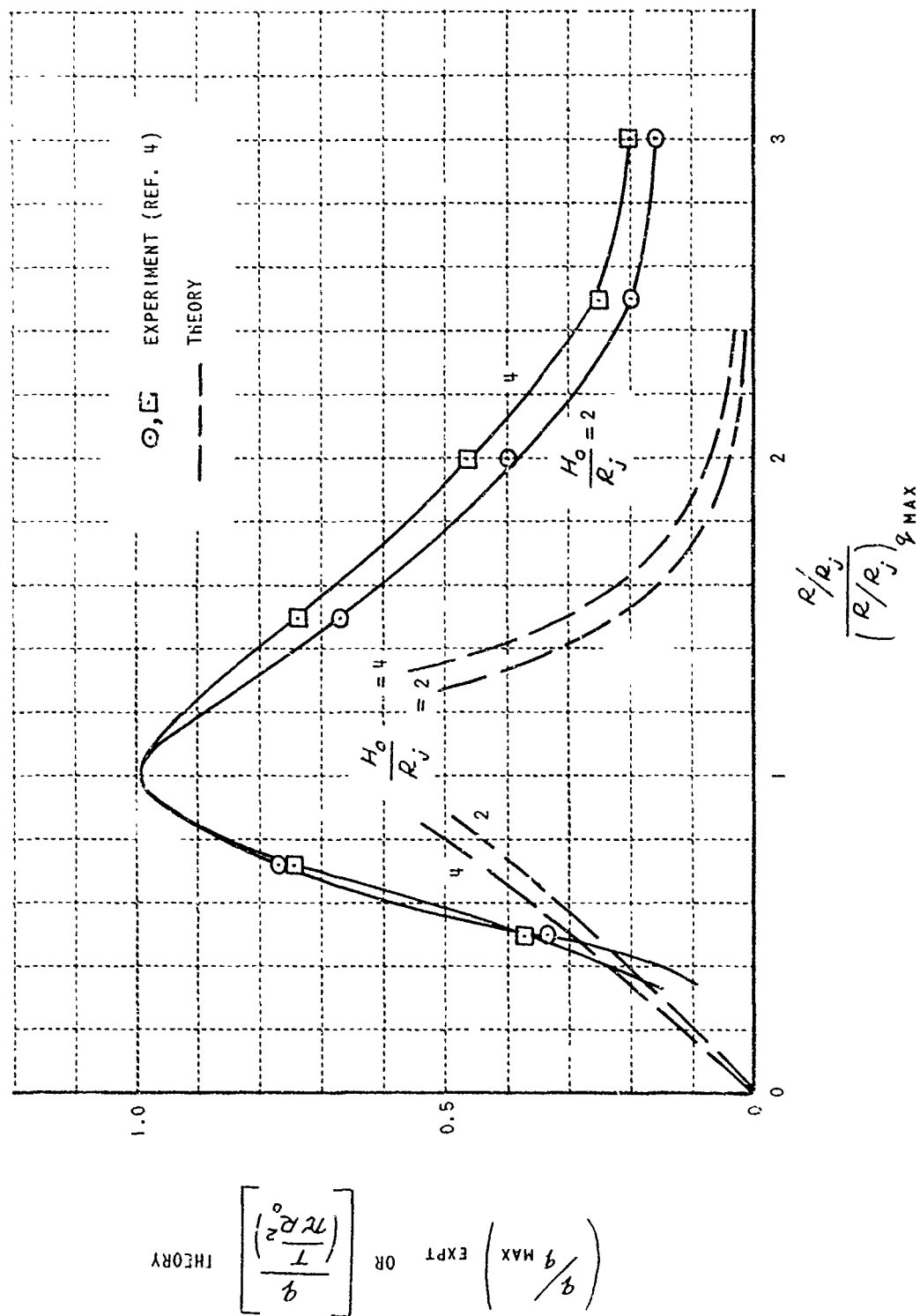
9

Fig. 4 COMPARISON OF EXPERIMENTAL AND THEORETICAL DYNAMIC PRESSURE
DISTRIBUTIONS IN THE FLOW PARALLEL TO THE GROUND

10

changed and, then, good correlation was obtained at distances greater than four diameters. The theory was found to be inaccurate for all disk loadings with ground separation distances of less than four diameters.

In addition to the flow field in the jet, it has been shown that the un-flared, cylindrical vortex sheet model provides a good qualitative description of the upwash field outside of the jet. The theoretical results of Reference 8, shown in Figure 5, indicate that the magnitude of the dynamic pressure in the upwash is a sizable fraction of the maximum dynamic pressure at the jet exit, even at a distance of two jet radii from the axis of the jet. It is interesting to note that, on the basis of data presented in Reference 4 and reproduced in Figure 6, the dynamic pressures theoretically predicted for the upwash are sufficient to suspend particles of the sizes which have been observed. The existing theory is lacking, however, in that it predicts the particles to be suspended relatively close to the outer rim of the jet cylinder while, in fact, they are observed to be several radii away from this rim. Again, a flared jet model might be expected to resolve this quantitative difficulty.

Ground Boundary Layer

The problem of the boundary layer development along the ground plane under an impinging jet is a difficult one and there are no complete solutions for either a laminar or turbulent flow in the literature. Solutions are available, however, for flows which are related to the present problem; for example, the solution of an axially symmetric stagnation flow on a plate. It is shown in Reference 9 that the flow obtained by the solution of the classical stagnation problem is the same as the potential flow in a small center region of an impinging jet. While this solution would apply near the center of the impinging jet, our interest is primarily concerned with the flow some distance away from the jet stagnation point and, therefore, the practical value of this solution to the present problem appears limited.
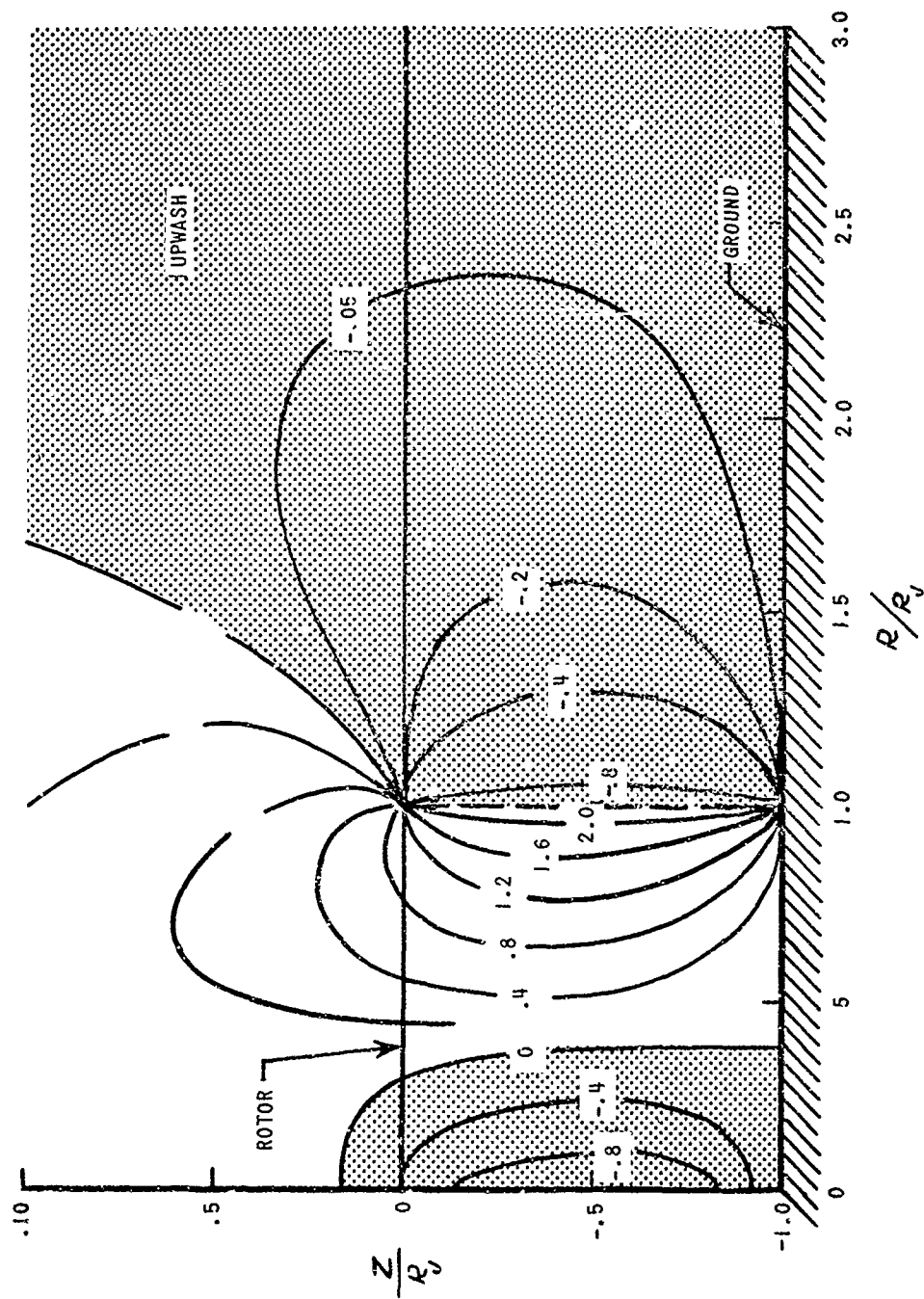
Fig. 5 CONTOURS OF THE INDUCED VELOCITY RATIO v/v_o FOR A TRIANGULARLY LOADED HOVERING ROTOR $\frac{H_o}{R_J} = 1$ (REPRODUCED FROM REF. 8)
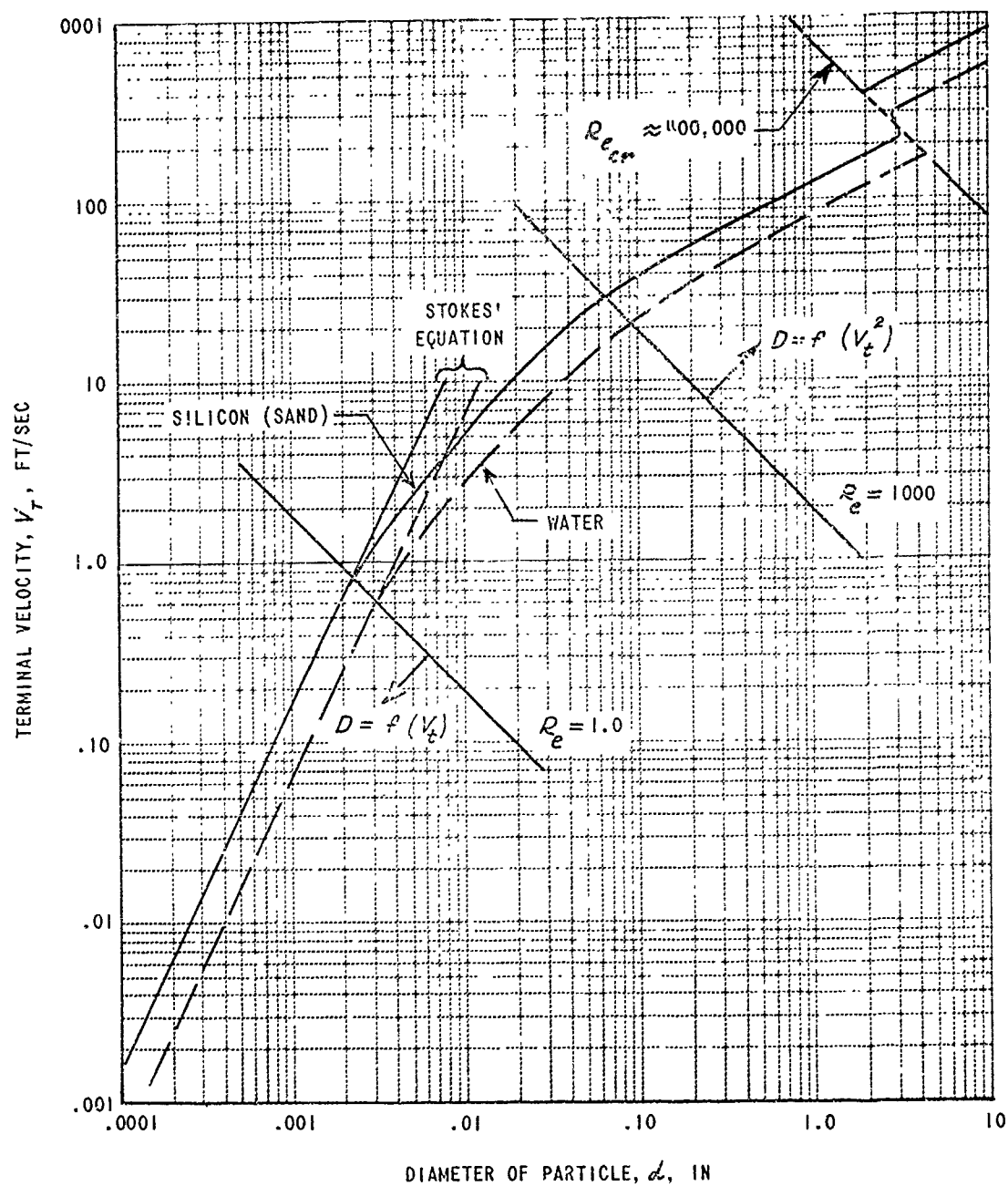
12

Fig. 6 TERMINAL VELOCITY OF PARTICLES VS PARTICLE DIAMETER
(REPRODUCED FROM REF. 4)

13

It appears that the best available approach to the present boundary layer problem is to make use of the two-dimensional solutions for a flow with a pressure gradient. These solutions would be applied in a step-wise fashion taking account of the local pressure gradient at each radial position. The validity of this approach is open to question since it assumes that no important three-dimensional effects occur other than the variations in the pressure gradient.

Forces on Ground Particles

There is a considerable body of literature dealing with the forces on bodies in a nonuniform flow; that is, flows characterized by a large velocity gradient or large shear as in a boundary layer. Of these, the theory of Reference 10 has direct bearing on the problem of the forces on a ground particle. This theory provides a solution for the pressure distribution on the meridian plane of a sphere in a flow with a linear velocity gradient, as a function of the velocity gradient. An estimate of the lift on the sphere due to the velocity gradients has been obtained by assuming the flow over the sphere is two-dimensional and by integrating the pressure distribution over the surface of the sphere. The results obtained indicate that there is a considerable lift force on the sphere due to the velocity gradients which tend to lift this sphere toward the higher velocities.

Hall's theory (Reference 10) for spheres in uniform shear flow holds for an unbounded flow, but the present problem is concerned with forces on particles near a wall. There are no nonuniform flow theories including the effect of a wall, but an estimate of the wall effect can be obtained using the uniform flow theory of Reference 11. This solution shows the effect of the wall is to distort the flow over the sphere and cause an additional lift force. This additional lift due to the wall effect can be added to the lift due to velocity gradients to obtain an estimate of the total lift on the sphere.

Using the available nonuniform and uniform flow theories of References 10 and 11, respectively, the lift and drag have been calculated for a spherical particle in contact with the ground plane and immersed in a typical laminar boundary layer. The calculated lift force was used to determine the size of the

14

particles that could be just lifted by various streams and the calculated drag force was used to estimate the particle sizes that will roll along the ground. The results of these calculations are presented in Figure 7 which plots the radius of a sphere, nondimensionalized by the boundary layer thickness, versus the particle weight per unit cross-sectional area, nondimensionalized by the dynamic pressure. One interesting feature of these results is that, for a given particle size, the lift and drag forces are quite comparable in magnitude. Another is the fact that both the lift and drag curves reach a maximum for r/δ = 0.4 - 0.6. This latter result indicates that the particles that have a diameter about equal to the boundary layer thickness would be entrained more easily than smaller or larger particles. This is roughly in agreement with the experimental results presented in Reference 4.

The lift and drag forces that have been calculated for a spherical particle demonstrate two mechanisms for particle entrainment. The drag force, by itself, causes the particle to roll along the ground so that subsequent elastic impacts with other particles could cause it to bounce into the jet stream. Due to the random nature of this process, it is difficult to speculate on its importance in the downwash impingement problem. It can be shown, however, that the rolling energy, in some cases, is large enough to bounce a particle several feet.

The lift force on a particle in the boundary layer is large enough to lift fairly large objects free of the ground plane. To illustrate, consider a downwash velocity of 60 fps and a laminar boundary run of 10 ft. which yields a laminar boundary thickness of about one-half inch. Taking the ground particles to be the density of sand or gravel, $\rho_s g$ = 120 lbs/ft.^{3}, the corresponding value of the abscissa is $\frac{\rho_s g \delta}{\rho/2 \ V_o^2} \cong 0.50$. Figure 7 shows that all particles with a radius such that $r/\delta < 0.009$ will be rolled out along the ground because of the drag force on the particle. For all particles in the range, $0.009 < r/\delta < 0.18$, the lift is less than the weight and the drag is smaller than the static friction, so that they are not entrained. For those particles in the range, $0.18 < r/\delta < 0.21$, the lift is still less than the weight, but the drag exceeds the static friction and these are rolled along the ground. For those particles in the range, $0.21 < r/\delta < 0.72$, the lift exceeds the weight and the drag exceeds the static friction, and these particles will roll and be lifted from the ground plane.
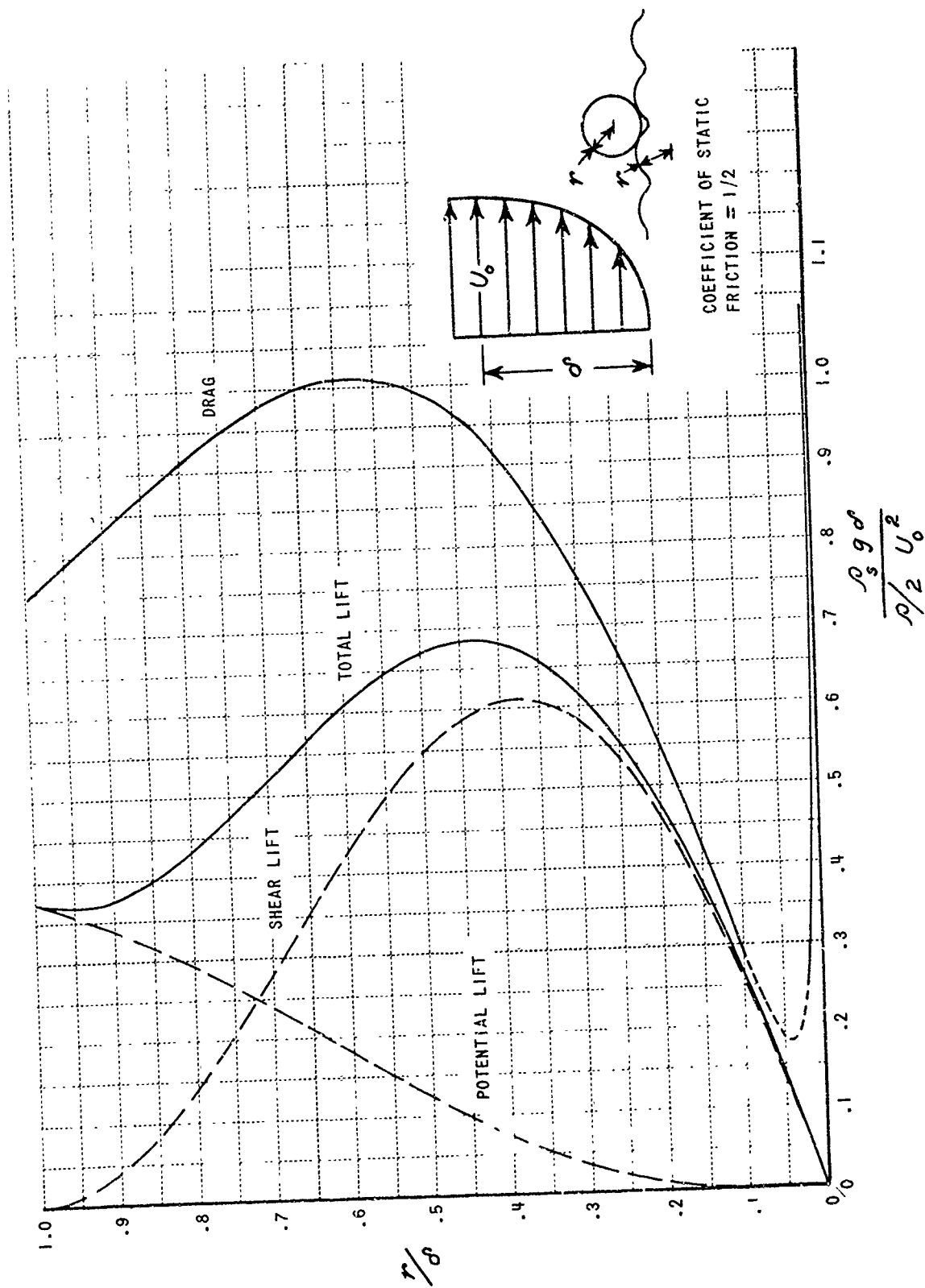
15

Fig. 7 CRITICAL PARTICLE SIZES FOR ENTRAINMENT IN A LAMINAR BOUNDARY LAYER

16

As a further illustration, consider the same flow conditions and particle density, but now with a laminar boundary layer run of 20 ft. This corresponds to a boundary layer thickness of δ = 0.7 in. and $\frac{\rho_s g \delta}{\rho/2 V_o^2} \cong 0.8$. Again at this station the very small particles, $r/\delta < 0.005$, are rolled out along the ground and the particles defined by $0.005 < r/\delta < 0.34$ are unaffected. Those falling in the range $0.34 < r/\delta < 0.94$ are rolled along the ground but, at this station, no particles are lifted from the ground directly.

These two illustrations lead to the interesting and important conclusion that there will be discrete ground areas under an impinging jet which will be critical in the particle entrainment problem. Considering the area near the jet stagnation point, it is noted that due to the laminar boundary layer thickness, δ , the parameter $\frac{\rho_s g \delta}{\rho/2 V_o^2}$ varies as $\sqrt{\frac{R}{V_o^5}}$ where R is the radial station. Figure 4 shows that near the stagnation point, the velocity in the inviscid flow, V_o , is small so that the parameter $\frac{\rho_s g \delta}{\rho/2 V_o^2}$ is large. Figure 7 demonstrates that, except for very fine dust, no entrainment will occur until $\frac{\rho_s g \delta}{\rho/2 V_o^2} \cong 1.0$, so that particles near the stagnation point will be unaffected.

Now in considering radial stations progressively further from the stagnation point, the data of Figure 4 shows that the velocity, V_o , will increase until at some station, determined by the disk loading, $\frac{\rho_s g \delta}{\rho/2 V^2} < 1.0$ and entrainment will begin by the drag mechanism. Particle sizes of $r \cong 0.6 \delta$ will begin to roll at this station. Now for radial stations beyond the critical station, entrainment will continue and progressively larger and smaller particles will be entrained by the drag mechanism. This is true only if the parameter $\frac{\rho_s g \delta}{\rho/2 V_o^2}$ continues to decrease, or equivalently if the velocity V_o continues to increase faster than the fifth root of the radial station. If the disk loading is such that $\frac{\rho_s g \delta}{\rho/2 V_o^2}$ attains values of 0.7 or less, particle entrainment by the lift mechanism will begin.

Near the radial station corresponding to the peak velocities, the boundary layer will begin to thicken rapidly as the velocity decreases. The parameter $\frac{\rho_s g \delta}{\rho/2 V_o^2}$ will increase with radial station, and a region should occur corresponding to $\frac{\rho_s g \delta}{\rho/2 V_o^2} \cong 0.3 - 0.6$ where certain particles will not be entrained.

17

Some particles rolled out from the central ground and not yet entrained will tend to pile up in this region since the aerodynamic forces are not sufficient to maintain the motion. This piling up will continue with increasing radial station and simultaneously only the very smallest and largest particles will be entrained.

It is important to note that these examples are qualitative, owing to the approximations used. In particular, the methods used to estimate the aerodynamic forces and the assumptions of a laminar boundary layer are open to question, and a more rigorous development is necessary before quantitative estimations can be made. These results do, however, illustrate the mechanisms for particle entrainment and are of qualitative significance.

In the foregoing discussions, no consideration has been given to the possible effects of discrete trailing vortices as obtained with a finite number of rotors or propellers. In contrast to the case of a pure jet of air in which the vortex filaments are infinitesimal in strength and in separation, a rotor having a finite number of blades has strong vortex filaments with finite spacing. It has not been established whether or not discrete trailing vortices can result in local velocity maximums of sufficient magnitude to have an important effect on the impingement problem.

In addition to the above, no consideration has been given to the influence of a nonuniform disk loading other than to note that a uniform jet was observed to produce erosion and entrainment similar to that produced by a ducted fan. It should be noted that the data in Reference 4 are not entirely definitive on this point, as there were observed differences in the dynamic pressure at which erosion began for a ducted fan and a uniform jet. However, these same data exhibit equal differences due to size of the jet and, therefore, it cannot be ascertained whether disk load distribution or scale caused the discrepancies. For quantitative estimates of incipient erosion, consideration must be given to the influence of disk load distribution and scale.

18

Jet Flap and Deflected Slipstream Configurations

The previous remarks have been directed toward solution of the downwash impingement problem for configurations using a rotor, propeller, or jet engine to obtain lift. The solution of the downwash impingement problem for the jet flap configuration, the deflected slipstream configuration, and their variations should have the same development as previously outlined. That is, the flow field about the configuration in proximity to the ground should be determined first and, then, the boundary layer solution should be obtained and, finally, the forces on the ground particles should be considered. The important item lacking in this sequence is an adequate representation of the inviscid flow field.

Consideration has been given to the aerodynamic characteristics of the deflected slipstream and jet flap configurations in ground effect. The work has been primarily concerned with determining the effects of ground proximity on lift. The work reported in References 12, 13, and 14 shows there is a detrimental ground effect on both of these configurations, apparently stemming from a choking of the flow beneath the wing. The chief feature of this flow, illustrated on Figures 8 and 9, is that the physical flap or the jet flap blocks the flow so that a vortex motion is set up beneath the wing. The potential importance of the vortex motion below the wing is quite apparent in Figures 8 and 9. The vortex causes a reverse flow along the ground plane so that particles might be picked up and reingested in the propeller flow or in the jet engine.

There have been no theoretical investigations of the deflected slipstream configuration in ground effect which takes account of the blocking effect. For the jet flap configuration in two dimensions however, in Reference 13, Huggett has investigated the conditions under which the flow is blocked. He is able to predict the maximum lift in ground effect with good accuracy. A logical step in the downwash problem would be to use Huggett's model to investigate the magnitude of the velocities at the ground for the jet flap configuration. Because the model is quite general, it should also provide qualitative estimates of the deflected slipstream flow field. This would then enable one to proceed with an analysis of the boundary layer and particle dynamics.
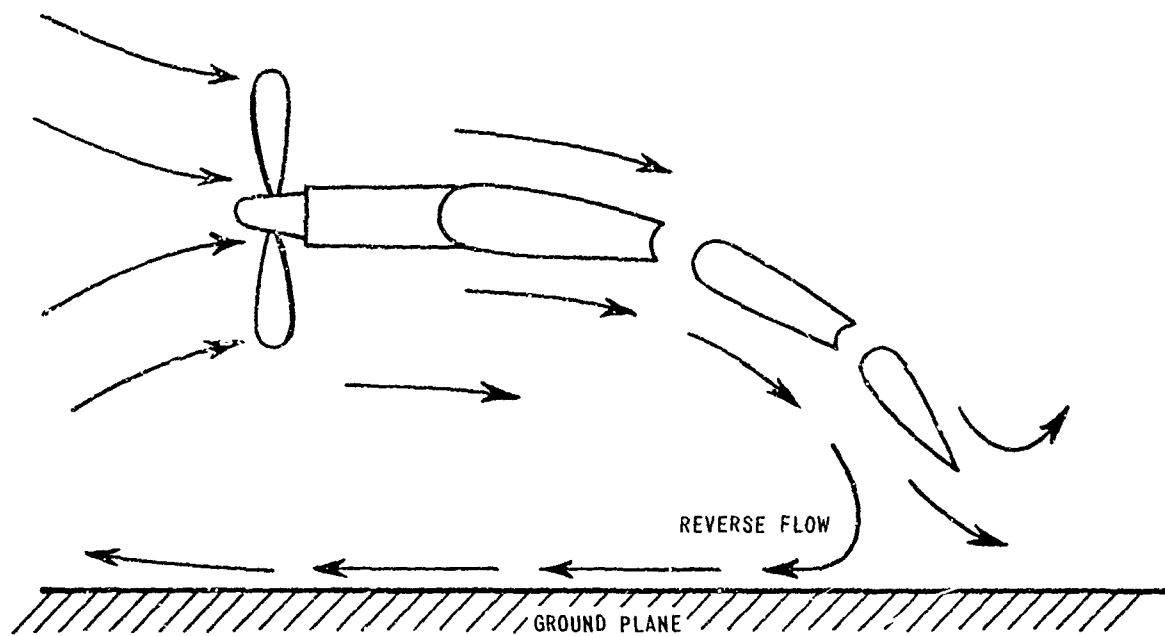
REVERSE FLOW

GROUND PLANE

Fig. 8   FLOW FIELD OF DEFLECTED SLIPSTREAM CONFIGURATION IN GROUND EFFECT
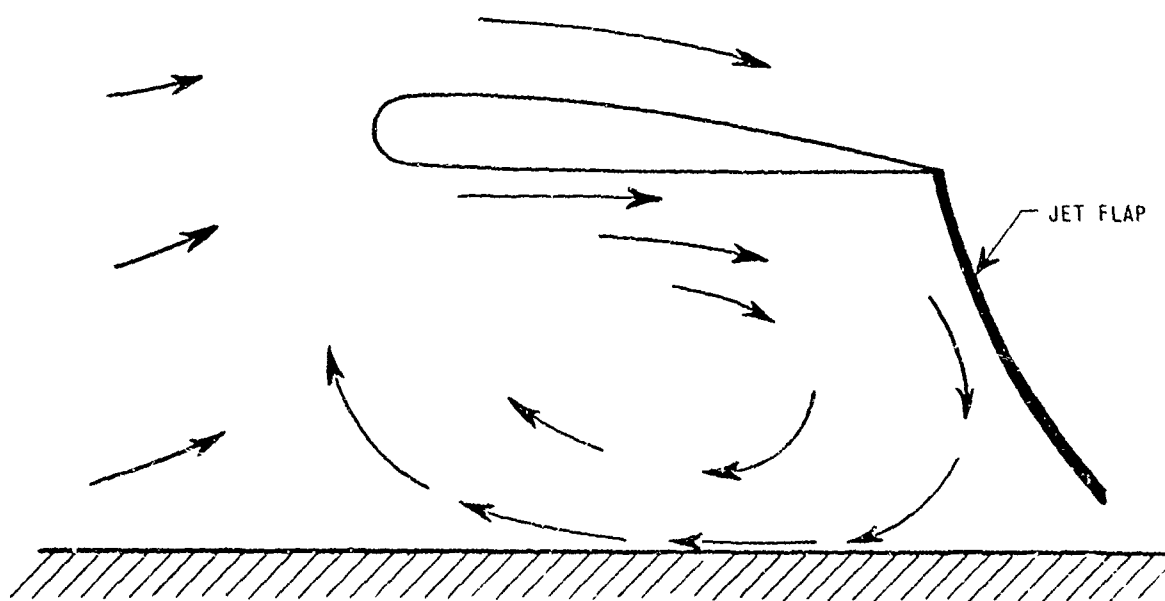

JET FLAP

Fig. 9   FLOW FIELD OF THE JET FLAP CONFIGURATION IN GROUND EFFECT

20

III   PROGRAMS SUGGESTED TO INVESTIGATE VARIOUS ASPECTS OF
THE DOWNWASH IMPINGEMENT PROBLEM

This section presents the various suggestions made to: (1) obtain a better understanding of the problem, (2) to investigate ideas that have been suggested to reduce the entrainment and detrimental effects of particles, and (3) investigate ideas that have been suggested for avoiding entrainment of objects by the downwash. In this section, the suggested programs and brief outlines of their objectives are presented. No attempt is made in this section, however, to evaluate their relative merits.

A.   Research Directed Toward a Better Understanding of the Problem

There are three basic requirements for obtaining a better understanding of the downwash impingement problem: first, the flow fields in the vicinity of VTOL vehicles must be defined more accurately; secondly, it must be possible to make better predictions of the aerodynamic forces on sand, dust, pebbles, etc., both before and after entrainment into the flow; and, finally, characteristic particle trajectories must be obtained for various configurations and operating conditions. The following research programs are suggested for extending the basic knowledge already existing in these areas. It should be pointed out that both theoretical and experimental investigations are required. A reliable theory would be useful in predicting the effects of downwash impingement for new configurations and different operating conditions, as well as for use in the evaluation of possible devices for alleviating the problem. It should be noted, however, that experimental results are always necessary for verifying theoretical conclusions. In addition, a solution obtained by experimental means may sometimes be obtained more readily than a theoretical solution.

21

1. Investigation of the Flow Field of a Jet in Ground Effect

A theoretical and experimental investigation should be undertaken to determine the flow field of a jet in ground effect which would be applicable for the study of vehicles utilizing rotors, propellers, and ducted fans. Accurate flow data are required for investigating initial particle entrainment and for finding the trajectories of entrained particles. The nature of the boundary layer development under an impinging jet, as well as the nonviscous flow outside of the boundary layer, should be adequately defined.

2. Investigation of the Effects of Individual Tip Vortices

Low solidity rotor and propeller blades give rise to wake patterns which include discrete helical vortices. Passage of these vortices over a fixed point on the ground gives rise to fluctuating induced velocities. A research investigation is required to determine the significance of these unsteady effects in the downwash impingement problem.

3. Investigation of the Flow Fields of the Deflected Slipstream and Jet Flap Configurations in Ground Effect

The flow fields of the deflected slipstream and jet flap configurations in ground effect should be determined theoretically and experimentally. These flow fields would be used as the basis for studying the resulting entrainment of dust and debris and the trajectories of the entrained particles.

Experimental data which exist on the flow fields of these aircraft are inadequate for a quantitative investigation of their downwash impingement problem. Existing experimental results do indicate, however, that the flow is physically blocked by the flap system of these configurations and a region of reverse flow is established beneath the wing. This results in the existence of a rotational flow beneath the wings of these configurations which must be taken into account in any analytical treatment of the problem.

22

4. Investigation of the Mechanism of Particle Entrainment

Theoretical and experimental investigations should be undertaken to determine the forces on a particle in the boundary layer created by the downwash. These data should be obtained in order to provide an understanding of the conditions for the initial entrainment of particles.

Consideration would be given to evaluating the lift on objects which results from the velocity gradient normal to the ground, as well as that due to the distortion of the flow over the object. Experimental observations have indicated that debris might be propelled into the airstream by a series of elastic collisions (sometimes called "saltation"). There is a need for studying the relative importance of the above-mentioned effects in developing adequate methods for predicting initial particle entrainment.

5. Investigation of Particle Trajectories for Typical VTOL Configurations

The trajectories of entrained particles should be studied in order to determine where damaging particles are first entrained and to suggest means for alleviating the problem. The effect of the aerodynamic forces developed cn the particle due to particle motion should be studied. Also, the effect of particle size, shape, and density should be evaluated.

B. Ideas That Have Been Suggested for Avoiding Entrainment of Objects By The Downwash

Prevention of entrainment and/or transport of dust and debris might be accomplished by several means; e.g., modification of the air flow along the ground, physical separation of the ground from the downwash, and distortion of the over-all flow field. Demonstration, experimental optimization, and mechanical implementation of these methods would be the objectives of the programs outlined on the following pages.

1. Modification of Airflow Near the Ground

   a. Investigation of Means for Reducing Velocities and Velocity
      Gradients in the Boundary Layer Along the Ground Due to Downwash

   A potential means for controlling the particle entrainment process
is to utilize boundary layer separation to lower the velocities acting on particles
on the ground. Obstacles such as concentric rings, snow fences, etc., might be
effective in producing separation. Another method for modifying the flow would
be to supply low energy air at the ground to cause thickening of the boundary
layer.

   In order to evaluate these methods, it is necessary to study the
particle forces and motions in separated flow and it is recommended that pertinent
data be obtained in an experimental investigation.

   b. Investigation of Effects of Secondary Flows

   It is noted that if particles tend to accumulate in the core of a
vortex, it might be possible to trap the particles within the vortex. These
secondary flows could be established by distributing shaped objects on the
landing area. It is suggested that a research program be undertaken to investi-
gate the feasibility of causing and exploiting secondary flows along the ground.
The emphasis should be on determining the vortex strength and vortex trajectories.

2. Optimization of Ground Covers

   a. Investigation of Physical Covers

   A large mat placed over the ground effectively prevents particle
entrainment. It has been found, in general, that the mat must be many rotor
diameters in extent to avoid particle entrainment. Cover sizes required should
be determined as a function of disk loading for the range to be encompassed by
VTOL aircraft.

24

As suggested by NASA, portable perforated plates supported a short distance above the ground might reduce the dynamic pressure of the downwash passing through them and, thus, decrease the amount of sand, dirt, and debris which would be picked up. Optimum plate size, perforation form, and height above ground should be determined.

Research with thrust reversal devices indicates that a deflector which has a diameter of about 1.8 times the jet diameter works effectively in reversing the momentum within the jet. This characteristic should be advantageous for ground covers and should permit a radical reduction in cover size. It is suggested, therefore, that ground covers patterned after thrust reversers be investigated.

   b. Investigation of Means For Increasing Soil Cohesion
      or Laying a Ground Cover by Spraying

The surface of the ground might be oiled or prepared with a suitable chemical spray as a means of preventing erosion.

It should be possible to form a low density, rather thick plastic foam covering on the ground that could be used three to five minutes after spraying. Since this foam weighs about 2 lbs/ft.^{3}, the weight of the foam covering a 1000 ft.^{2} area would be approximately 80 lbs. The foam covering has an allowable compressive load of 5760 lbs/ft.^{2} and should thus be capable of supporting VTOL aircraft. It is suggested that a foamed ground cover be investigated for use in eliminating particle entrainment.

   3. Development of Lightweight Droppable Physical Covers, Flow Separators, etc.

      a. Investigation of Inflatable Structures

It is believed that inflatable structures can be used as ground covers, obstacles for producing boundary layer separation, thrust reversers, and to produce vorticity for trapping particles. Such structures or membranes could possibly be droppable and require no ground crew. Inflatable structures appear to offer promise for this application with respect to the following:

25

(1) spreading the membrane,

(2) shaping the impingement area.

b. Investigation of a Staking System for Air-Dropped Covers

Air transportable covers, flow separators, etc., would be light-
weight by necessity and would, thus, be easily moved by the downwash unless
anchored to the ground. Investigation of suitable staking systems that require
no ground crew is suggested.

4. Development of Operational Techniques

a. Investigation of Aerial Sweeping

Prior to landing in an unprepared area, the VTOL aircraft might
fly by the proposed landing spot several times and attempt to blow dust and
debris away.

The aerial sweeping technique would probably only be of value for
very special ground conditions. For example, it might be effective for removing
small quantities of loose gravel or debris from rock or hard ground. If
appreciable amounts of sand or dust were present, this technique would be
poor from the pilot visibility and loss of concealment standpoints.

b. Investigation of Formation Flying to
     Obtain More Desirable Flow Patterns

Several VTOL aircraft might be flown in a formation which could
result in a more favorable flow pattern from a downwash impingement standpoint.

c. Investigation of the Application of Jump Take-off Technique

During take-off, a helicopter would be warmed up and run up to an
overspeed condition in low pitch in order to minimize the downwash velocity.
The rapid application of collective pitch might then permit the helicopter to
be lifted out of the ground effect region before becoming engulfed by flying
debris. In order to determine the usefulness of this technique, it would be
necessary to compare the time required to lift debris to the time required for
the helicopter to get away from the take-off point. An experimental investigation
is suggested.   26

C. Ideas That Have Been Suggested to Minimize the Entrainment
   and Detrimental Effects of Particles

The avoidance of particle entrainment would be the optimum solution of the
downwash impingement problem. Even if this optimum solution is not obtainable,
it may still be possible to greatly reduce the amount of entrained particles
and alleviate their detrimental effects. This may be accomplishable by changing
the vehicle design and/or the development of systems whereby the pilot and air-
craft can satisfactorily operate. Research programs which are directed toward
reducing the entrainment of particles and alleviating their detrimental effects
are listed below.

   1. Reduction of Particle Ingestion by the Engine

      a. Application of Various Particle Separators
         at the Engine Air Intake

An investigation should be conducted to determine if particle
separators, such as settling chambers, cyclone separators, centrifugal separators
impingement separators, fibrous and dust filters, could be used to preclean the
air without causing an appreciable power loss.

      b. Application of an Electrical Precipitator for Particle Removal

Preliminary calculations indicate that an electrical percipitator
could be used to preclean the air before entry into an engine. For example, a
power supply similar to that developed for the Helicopter Static Discharge
Program, Contract DA-44-177-TC-652, might be suitable. An investigation should
be conducted to determine if a practical application of an electrical precipitator
can be realized to preclean the engine intake air.

      c. Investigation of the Use of Rotor Blade Cuffs
         to Eliminate the Upwash at the Engine Intake

An investigation should be conducted to determine if cuffs at the
root of the rotor blade would change the direction of flow near the fuselage
when the helicopter is operating near the ground. Such cuffs could be used in

27

conjunction with an upward-facing air scoop in hovering to obtain a cleaner airflow to the engine. The success of the system would be dependent on the importance of dust introduced by recirculation near the fuselage as compared to that caused by the inherent upwash at the center of the rotor.

   d. The Use of Pop-Out Fuselage Skirts to Block the Upwash

It is recommended that the use of fuselage skirts be investigated to determine if the amount of dust and sand particles in the airflow near the engine inlet can be reduced by blocking the upwash flow near the fuselage.

   e. Redesign of Critical Engine Parts to Withstand the
      Abrasive Effects of Sand and Dust Particles

The jet engine has shown remarkable reliability when subjected to environments which contain a considerable amount of foreign objects. Deterioration of engine parts, however, does occur due to the abrasive effects of the particles passing over the engine parts. A program should be conducted to determine if highly abrasive-resistant coatings can be applied to critical engine components, such as the leading edges of the turbine blades.

2. Basic Design Modifications to Reduce Particle Entrainment

   a. Reduction of the Dynamic Pressure of Impinging Airflow
      by the Use of Multiple Jets

The mixing of a jet with the ambient air causes it to spread as the distance from the nozzle increases. This spreading causes a decrease in the jet dynamic pressure. The ratio of the reduced dynamic pressure to the exit dynamic pressure is proportional to the ratio of the exit diameter to the distance from the jet exit. Thus, with a given exit dynamic pressure and ground clearance, a greater reduction in dynamic pressure is obtained with a smaller diameter jet. It is suggested that a research program be conducted to determine if the replacement of a single jet by a number of smaller jets developing an equivalent amount of thrust markedly reduces the entrainment of particles.

28

b. Reduction of Particle Entrainment by Diminishing
the Intensity of the Trailing Vortices

It is suggested that an investigation be conducted to determine if
boundary layer control, end plates, or vortex generators could be used to reduce
the intensity of the trailing vortices and, thus, the entrainment of particles.

3. Basic Design Modifications to Minimize the Effects of Entrained Particles

a. Investigation of the Beneficial Effects Obtained by an
Air Jet Flowing in a Spanwise Direction at the Blade Tip

The rotor would be fitted with air jets at the tip, blowing in the
spanwise direction away from the tip. The objective of employing such jets is
to increase the effective span of the blade in order to contain the entrained
particles in a cylinder beyond the rotor tip.

b. The Use of Landing Gear Doors to Redirect the
Downwash Flow and Entrained Particles

Landing gear doors of the proper size and shape might be used with
a fan-in-wing-type configuration to deflect the downwash outward, thus blowing
the entrained particles away from the aircraft. This would also tend to minimize
recirculation.

c. The Use of Pop-Up Fences on Tilt-Wings to Redirect the Downwash

The wings of tilt-wing configurations would be equipped with fences
to deflect the flow away from the fuselage while operating near the ground.
These fences would be retracted in normal flight to avoid a drag penalty. The
modified flow should give better pilot visibility, minimize recirculation, and
minimize the effects of entrained particles on the aircraft.

d. Deflectors to Redirect the Downwash Flow of
Ducted Fans Mounted at the Wing Tip

Retractable deflectors would be used to redirect the downwash of
ducted fans to an outward direction when operating near the ground.

Redirection of the flow would tend to minimize recirculation, loss
of pilot visibility and the damaging effects of entrained particles. These
deflectors could also be used for lateral aircraft control.

IV RECOMMENDED RESEARCH INVESTIGATIONS

This section of the report presents a series of recommended research investigations. All of the proposed programs are based on one or more of the suggestions presented in Section III. The investigations recommended are those believed to be most likely to result in significant advances in the understanding and control of the downwash impingement problem.

INVESTIGATION OF THE INVISCID FLOW FIELD AND
VISCID GROUND FLOW OF A JET IN GROUND EFFECT

Purpose

The purpose of this investigation is to obtain a more realistic analysis, including experimental verification, of the viscid ground flow and inviscid flow field under a hovering rotor-type configuration. This analysis will provide a basis for determining critical ground areas for particle pickup.

Discussion

The mechanism responsible for picking up and entraining ground particles in the downwash from a hovering rotor-type configuration is associated with the lift and drag forces on the particles immersed in the boundary-layer flow along the ground. These forces are determined by the magnitude of the velocity and velocity gradients in the boundary layer. An analytic treatment is required to predict the characteristics of the boundary-layer flow along the ground under a hovering rotor to provide a basis for considering means of controlling the entrainment. The classical boundary layer solutions for stagnation flows have bearing on this problem but are applicable only in the immediate vicinity of the stagnation point of the impinging jet. Approximate techniques are required for estimating the characteristics of laminar and turbulent boundary layers under an impinging jet, taking account of the pressure gradients along the ground plane.

In this connection, the distribution of pressures on the ground plane under an impinging jet can be, in principal, determined from the inviscid flow field for a hovering configuration in ground effect. The classical representation of this configuration in ground effect consists of replacing the rotor-slipstream system with an actuator disk and a constant diameter vortex cylinder

32

which intercepts the ground plane. In contrast, the actual system is characterized by a flaring vortex tube which never touches the ground. This classical model is apparently adequate for determining the effects of ground proximity at the rotor, but is inadequate for determining the flow field near the ground. This deficiency stems from neglecting the flaring of the slipstream at the ground and having the vortex tube intercept the ground. A theoretical investigation is required to provide an accurate prediction of the inviscid flow field along the ground plane and the information necessary to effect an analysis of the boundary layer along the ground. Here the emphasis should be on duplicating the jet characteristics influencing the ground flow, such as jet flaring, initial jet velocity, rotor height above the ground, etc.

A complementary program of experimental research should be pursued concurrent with the theoretical research, to guide the theoretical developments and to provide a continuing appraisal of the theoretical assumptions. The experimental emphasis should be to define the jet flaring due to ground effects and to determine the ground boundary layer characteristics in important ground regions.

Suggested Scope of the Proposed Research

A program of theoretical and experimental research is required to determine the velocity profiles and thickness of the boundary layer on the ground plane under a hovering rotor. The emphasis should be on obtaining a general method for predicting these boundary layer characteristics as a function of radial position along the ground plane in terms of the rotor disk loading and height above ground. In view of the complexity of the problem, it is recommended that the problem be treated by first determining the inviscid flow field including jet flaring, and then by using these results in an approximate boundary layer calculation. Experiments should be made both to guide and to check the theoretical developments.

INVESTIGATION OF THE FORCES ON GROUND
PARTICLES IN BOUNDARY LAYER FLOWS

Purpose

The purpose of this research is to determine experimentally the forces on
typical ground particles in a nonuniform flow simulating representative boundary
layers. This investigation should determine the forces on ideal and realistic
particles in contact with or near a wall to arrive at semi-empirical methods for
predicting the lift and drag on similar particles in boundary layer flows.
These data are required to provide a quantitative understanding of the conditions
necessary for the initial entrainment of ground particles in the downwash of
hovering VTOL configurations.

Discussion

Using the available theory, it has been demonstrated that the lift on a
spherical ground particle in a boundary layer flow is about equal to the viscous
drag, and can exceed the particle weight for certain particle sizes, boundary-
layer thickness, and stream velocities. This finding is of fundamental importance
in the problem of entraining ground particles in the downwash of VTOL configura-
tions since it indicates a mechanism for initially lifting the particles and pro-
vides a basis for considering means of controlling the phenomena. This investigation
will provide generalized force data for particles in typical boundary layer flows
and should demonstrate this mechanism for particle entrainment.

The only theories applicable to this problem are (1) an inviscid development
that treats the distribution of meridian pressures on a sphere in an unbounded
stream with a linear velocity gradient, and (2) an inviscid theory for a sphere
near a wall in a uniform stream. In contrast, the ground particle problem involves

a rough particle near a wall in a viscous stream with a nonlinear velocity gradient. The available theories are useful in that they demonstrate the important stream parameters influencing particle forces. However, they cannot be expected to yield quantitative estimates because they neglect the influence of separation on the particle forces, and do not consider the effects of nonuniform velocity gradient. In addition, no consideration is given directly to the influence of wall proximity in nonuniform flow.

It is apparent that further theoretical treatments are desirable; however, because of the complexity of the problem, it is doubtful that definitive results could be obtained pertaining to the particle entrainment problem. It is believed, therefore, that a program of experimental research is required to investigate the forces on particles in a flow with a nonlinear gradient of velocities. In this research the emphasis should be on determining the forces on bodies representative of ground particles in typical boundary layer flows, and generalizing the results so that estimates can readily be made of the forces on a variety of ground particles in laminar and turbulent boundary layers.

Suggested Scope of the Proposed Research

A program of experimental research is required to determine the forces on particles in a boundary layer flow, and to provide generalized data for predicting the forces on particles in a variety of boundary layers. In this research the emphasis should be to determine the particle forces in laminar and turbulent boundary layers with pressure gradients representative of those existing on the ground plane under a hovering rotor, and to determine the pertinent flow parameters fixing the particle forces. The research should include ideal particles as well as those typical of ground particles, and experiments should be made in a variety of known nonuniform flows.

INVESTIGATION OF PARTICLE PICKUP DUE TO A JET IN GROUND EFFECT

Purpose

The purpose of this investigation is to determine the regions on the ground plane under an impinging jet which are critical for particle pickup and entrainment in the jet flow, and to define those regions on the ground where ground modifications would alleviate the pickup problem.

Discussion

With the necessary data available to determine the characteristics of the viscous ground flow under a hovering rotor and the forces on particles immersed in this flow, an investigation should be made to definitively apply these results to predict those ground regions where particle pickup occurs. The investigation should be devoted to predicting these critical areas in terms of particle sizes and densities, and in terms of the rotor disk loading and height above the ground. One product of this phase of the work would be the establishment of military requirements covering soil conditions over which operations would be permissible with different configurations. Experiments should be made to verify the analysis and check the results.

With critical ground areas and particles so defined, the emphasis in the research should be to investigate means for controlling or eliminating particle pickup through ground modifications. Consideration should be given to achieving this by destroying the mechanism for initially picking up the particles. This might be done by locally thickening the boundary layer in critical regions, promoting boundary layer separation before pickup occurs, covering the critical ground areas, etc. The methods selected for controlling particle pickup should be checked with experiments to demonstrate their effectiveness.

36

Suggested Scope of the Proposed Program

An analysis should be made of the hovering rotor in ground effect to determine the ground areas and composition critical for particle entrainment, and methods should be investigated for preventing the pickup of ground particles. The results of the analysis and the recommended methods for alleviating the problem should be verified with suitable experiments.

INVESTIGATION OF THE INVISCID FLOW FIELD FOR THE DEFLECTED SLIPSTREAM AND JET FLAP CONFIGURATIONS IN GROUND EFFECT

Purpose

The purpose of this research is to make a theoretical analysis of the inviscid flow fields for the deflected slipstream and jet flap configuration in ground effect. This analysis should provide a basis for assessing the severity of the downwash impingement problem as it pertains to entrainment of ground particles, and for studying means of alleviating the problem.

Discussion

The available literature on these configurations in ground effect show that their overall performance is markedly diminished due to ground proximity. The mechanism for the loss in performance is, in both cases, associated with a flow blockage between the wing and the ground. In the deflected slipstream configuration, the flow tends to be blocked because the large flap deflections put the airfoil trailing edge close to the ground. In practical application of the jet flap configuration, the jet will impinge on the ground to block the free-stream flow. In both cases the flow blockage results in a vortex and a region of reverse flow along the ground circulating against the stream on the ground and with the stream at the wing. This recirculating flow provides a mechanism for lifting particles from the ground and recirculating them to impinge on the wing and power plants.

Suggested Scope of the Proposed Research

A theoretical investigation is required, treating the deflected slipstream and jet flap configurations, to determine the flow fields for these configurations in proximity with the ground. The emphasis should be on

determining the conditions for which the recirculating flow first begins and on determining the strength of the reverse flow as a function of configuration performance. Anticipating the future need for boundary-layer developments, the pressure distribution along the ground should be obtained. The theoretical results should be compared with the available data to assess their accuracy.

OPTIMIZATION OF GROUND COVER SIZE AND SHAPE

Purpose

The purpose of this investigation is to determine, by experimental means, the minimum required cover size to prevent particle entrainment. The minimum cover size shall be determined for shrouded and unshrouded configurations over a range of disk loading. The effect of contouring the ground cover on the minimum size shall also be investigated.

Discussion

It has been demonstrated that large mats laid over an unprepared ground are effective in preventing the entrainment of particles in the downwash stream. The size of ground cover required to prevent particle entrainment has not been adequately established. An investigation to describe the minimum cover size as a function of disk loading, disk diameter, downwash velocity, soil condition, etc. is required so that the various types of VTOL vehicles can be associated with a size of landing mat.

In addition to the investigations conducted with flat landing mats, investigations should be conducted to determine possible beneficial effects that might be gained by contouring. For example, investigations conducted with a thrust reverser shaped similar to a pop bottle cap have indicated that it can effectively reverse the momentum within the jet if its diameter is approximately 1.8 times the jet diameter.

Suggested Scope of the Proposed Program

Minimum cover size to prevent entrainment shall be determined for the

40

following range of operating parameters:

$$2 \leq \text{disk loading} \leq 250 \text{ psf}$$

$$1/4 \leq \left[\frac{\text{height of actuator}}{\text{characteristic actuator diameter}} \right] \leq 6$$

The effects, on the minimum cover size required, of simple contouring at the cover periphery shall be determined for a few shapes as a function of $\left(\frac{\text{depth of contour}}{\text{characteristic actuator diameter}} \right)$.

Tests should be conducted for all the basic types of soil conditions present in field operation, (sand, loose dirt, pebbles, etc.).

41

INVESTIGATION OF THE FEASIBILITY OF USING
FOAMING PLASTICS TO CONSTRUCT GROUND COVERS

Purpose

The purpose of this investigation is to establish the feasibility of using sprayed foaming plastics to construct ground covers for prevention of particle entrainment in the downwash of VTOL aircraft.

Discussion

Foamed-in-place plastics have been used for a number of years as a means of stabilizing stressed-thin-skinned structures. Recently, sprayed foaming plastics have been used to construct foamed radomes in which the plastic is the primary load carrying structure. It is believed that these recent advances in the field of plastics should permit the rapid construction of a landing mat which would be capable of resisting high downwash velocities and the crushing loads due to the vehicle landing gear. I addition, it is believed that the use of foamed plastic would permit easy and rapid contouring of the landing mat to obtain a desired cross sectional profile.

A single coating, approximately $\frac{1}{2}$ inches thick, of a polyester or polyether resin with an isocyanate foaming agent could be used within 3 to 5 minutes after spraying. Since this foam weighs approximately 2 lbs./ft.^{3}, the weight of foam covering a 1000 ft.^{2} area would be about 80 lbs. Since the foam has an allowable compressive load of approximately 5700 lbs./ft.^{2} it might withstand the landing gear loads of VTOL vehicles now in existance or those anticipated in the near future.

Since the plastic foams are transportable in relatively small containers, are light and can be applied by a single man to construct a ground cover of any shape, its proposed application (if feasible) would have many obvious advantages when compared to the use of large mats.

Suggested Scope of the Program

Tests should be conducted on representative unprepared grounds to determine if it is feasible and practicable to construct suitable ground covers using sprayed foaming plastics. Of the foaming plastics available on the commercial market, the one most suitable for this application should be determined. At least the following properties shall be determined for the materials used in these tests:

> Bearing strength
>
> Tension strength of cover-to-ground surface interface
>
> Mass increase due to soil adhesion
>
> Setting time

Materials proposed for this application should be identified with respect to the following characteristics:

> Chemical make-up and trade name (if any)
>
> Mass density (before and after solvent evaporation)
>
> Temperature limits for storage and use
>
> Weight of auxiliary equipment
>
> Toxicity
>
> Cost

43

INVESTIGATIONS OF VTOL DESIGN MODIFICATIONS
TO MINIMIZE THE EFFECTS OF DEBRIS ENTRAINED
IN THE DOWNWASH

Purpose:

The purpose of this program is the investigation of means to minimize
the effects of debris entrainment in the downwash of VTOL craft. Protection
of the pilot, his field of view, and the aircraft structure are the primary aims.

Discussion:

VTOL actuators (excluding the helicopter rotor) tend toward high disk
loading and small area. Hence, the possibility of redirecting the slipstream
by means of local structure exists. This redirection is only required in
hovering flight and therefore the structure could be retractable.

Suggested Scope of the Proposed Program:

Consideration shall be given to at least the following configurations
to determine if means of redirecting the slipstream can be provided.

>   Tilt-wing
>   Tilt-rotor
>   Deflected Slipstream
>   Rotatable ducted fan
>   Fan-in-wing

Modifications considered shall include at least the following, where appropriate:

>   Wing fence
>   Fence incorporated as part of landing gear door
>   Deflector mounted on actuator shroud

The effects of the proposed modifications on the control characteristics of
the VTOL aircraft considered shall also be evaluated.

INVESTIGATIONS OF HELICOPTER DESIGN MODIFICATIONS
TO REDUCE ENGINE DEBRIS INGESTION

Purpose:

The purpose of this program is the investigation of design modifications to reduce the ingestion of debris by the helicopter engine.

Discussion:

It is believed that entrainment in the flow field is the mechanism by which debris is placed in the vicinity of the engine inlet. It might be possible, therefore, to reduce the ingestion of debris by modifying the flow field in the vicinity of the engine.

Deformation of the flow field in the vicinity of the engine inlet by means of fuselage contouring might be one way to achieve the desired result. Consideration should be given to means for blocking the upwash near the engine inlet, for example, by means of retractable fences mounted on the fuselage. Consideration should also be given to distorting the flow field near the engine inlet by modifications to the rotor system (e.g., cuffs).

Limitations of present flow field theories preclude a purely theoretical approach. Consequently, experimental programs for defining the effectiveness of proposed modifications should be considered. If model tests are proposed, the scaling laws to be followed should be verified.

Suggested Scope of the Proposed Program:

A theoretical and experimental investigation shall be undertaken to determine if it is possible to modify the flow field near the engine air inlet to reduce the ingestion of debris. All proposed modifications shall be experimentally verified through the use of either full scale or model tests.

INVESTIGATION OF THE FEASIBILITY OF
PRECLEANING THE ENGINE INTAKE AIR

Purpose:

The purpose of this investigation is to determine if it is feasible to preclean the intake air to prevent debris ingestion and damage to the engine.

Discussion:

Under certain operations the power loss associated with the use of an air filter might be acceptable. For example, a helicopter while landing might be able to accept the power loss associated with the use of a simple type of air filter. Since this power loss would not be acceptable during normal operation, provisions would have to be made for cutting the filter in or out of the air supply system.

There is a possibility that a more refined type of filtering system could be developed that would not cause a loss of power in the propulsion device. For example, it can be shown that an electrostatic precipitator-type of filter drawing about two kilowatts of power could preclean the quantity of air required for a T-58 turbine at an air velocity of approximately 100 ft./sec.

It is suggested that it might be possible to develop an air filtering system suitable for use with certain VTOL configurations. The operational characteristics of the flight article should be considered in the evaluation of any proposed systems.

Suggested Scope of the Proposed Program:

By analytical techniques, determine the feasibility of precleaning the intake air of gas turbine engines.

Consideration shall be given to at least the following methods:

    Settling Chamber
    Cyclone Separator
    Centrifugal Separator
    Impingement Separator
    Filter
    Electrical Precipitator

Estimates shall be made of the penalties involved in the application of the cleaning device. These shall include at least the following:

    Installed weight
    Engine performance degradation
    Energy requirements
    Cost

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